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ScienceDirect
Energy Procedia 49 (2014) 1157 – 1164
Energy Procedia

SolarPACES 2013

Supercritical CO_2 cycles offer experience curve opportunity to CST in remote area markets

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Abstract

Experience curve approach has been used before to predict cost reductions in renewable power technologies. For wind and PV, this prediction came true but not for Concentrating Solar Thermal (CST). The CST has not been able to enjoy sufficiently high deployment rates and therefore has not been able to achieve significant cost reductions. This paper examines the technical reasons for the relatively slow CST uptake over the last two decades and how this can be remedied in the future using different technology.

Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
Final manuscript published as received without editorial corrections.
Keywords: Concentrating solar thermal; supercritical CO_2 Systems; experience curve

1. Introduction

We have known for a long time that unit production costs decrease with accumulated learning of the production workers. For airframe manufacturing this cost reduction was a constant fraction for every doubling of the production volume[1]. This phenomenon has become to be known as the learning curve. In 1960s, the Boston Consulting Group proposed a generalization of the learning curve approach to whole industries by combining learning with technological improvements and product size effects and called it the "Experience Curve". Thousands of experience curves were plotted by the staff of the Boston Consulting Group in many industries, including integrated circuit manufacturing, life insurance policies, bottle caps, refrigerators and polystyrene molding resin and motorcycles, to demonstrate that the unit cost for a product decreased with increasing market size due a combination of learning, technological improvements and scale advantages[2]. It had been predicted that similar mechanisms would be effective to reduce the cost of renewable power[3]. These predictions came true for some renewable power technologies but not for all. Concentrating Solar Thermal (CST) power is a notable example for those

Selection and peer review by the scientific conference committee of SolarPACES 2013 under responsibility of PSE AG.
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doi:10.1016/j.egypro.2014.03.125

renewable power generation sectors that have not been able to build up an experience curve and enjoy consequent cost reductions. There are technical reasons for this as explained further below.

Nomenclature

C	Unit cost
C_o	Cost of the first unit
CST	Concentrating Solar Thermal
LEC	Levelised Electricity Cost
m	Exponent of the experience curve
PR	Progress ratio (the rate at which the costs decline for every doubling of the cumulative production)
PV	Photovoltaic
Q	Cumulative production
sCO2	Supercritical CO2

IEA[3] and Junginger[4] provide comprehensive reviews on the use of the experience curve method to predict future cost reductions in different renewable technologies, e.g. on-shore and off-shore wind farms and photovoltaics. The only CST experience curve study referred to in these references is a consulting study[5] based on the SEGS data of the 1980s.

The results on PV and wind power studies provide convincing evidence that the experience curve approach is a useful tool. However, it has two major limitations, which are important to its use for CST cost predictions:

- The experience curve approach is more suitable for modular systems with relatively small module sizes. The PV panels or wind turbines are good examples.
- It is possible to predict how the cost will come down with increased market diffusion but it is not possible whether that diffusion will take place.

With these caveats in mind, the experience curve for renewable power installations may be expressed as follows:

$$C = C_o Q^m \quad (1)$$

In equation (1), C_o is the cost of the first unit produced and C is the unit cost after Q units have been produced. The exponent m is usually defined in terms of the Progress Ratio. The Progress Ratio (PR) is defined as the rate at which the costs decline for every doubling of the cumulative production, i.e. $PR = 2^m$. The magnitude of the Progress Ratio partly depends on the type of technology but is generally lower for modular technologies.

2. The units for measuring experience

Published studies using experience curve for renewable energy are based on the installed power as the unit to measure the production volumes. For example, Figure 1 shows the decrease in the silicon-based PV module prices over the last three decades with the cumulative production measured in number of megawatts. The Progress Ratio estimates for PV module experience curves are around 80% and the differences between different estimates are usually due to the differences in the analysis window [4].

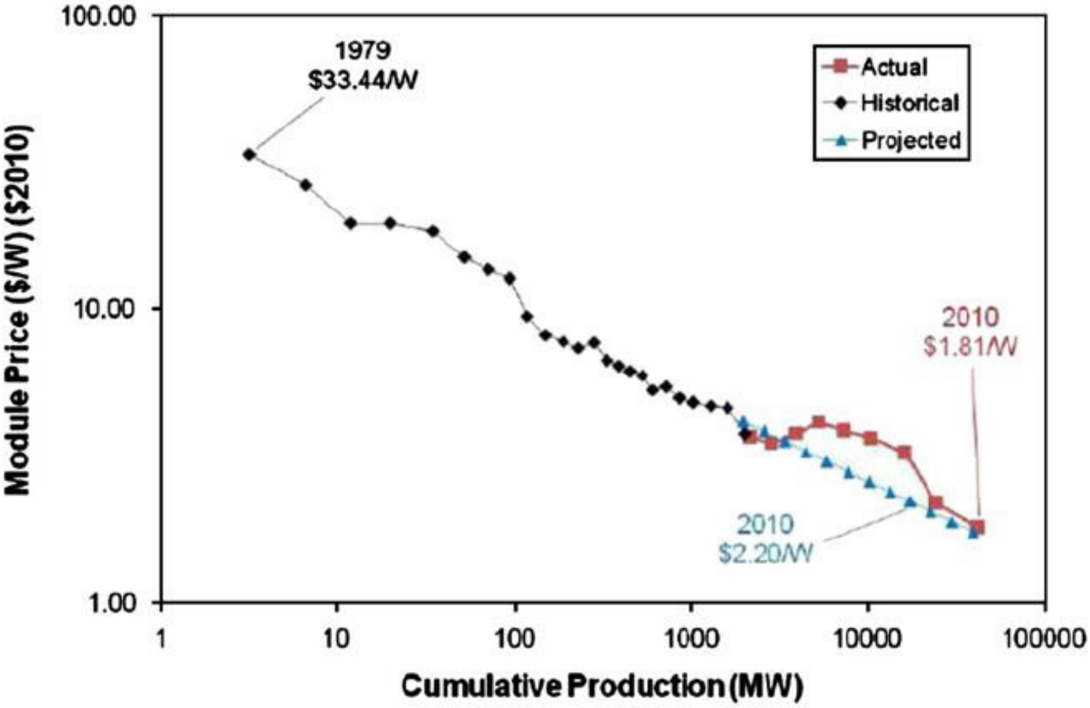

Figure 1. Module prices as a function of global cumulative installed capacity[6]

For a modular technology like PV modules, installed capacity is a good proxy for experience. It may not be as useful a proxy for CST experience. This is because a typical CST installation is much higher than that in PV. The unit size is important because the experience gained by installing 10000 of 20-kW installations by a group of competing suppliers would arguably have a larger effect on the industry experience curve compared to a single 200-MWe installation, although both correspond to the same increase in installed capacity.

A more appropriate representation for the experience, especially in CST, could be the number of installations. Published reports on PV experience do not mention installation numbers but estimates can be made. According to Feldman et al[7], the 152,000 PV systems installed in USA between 1998 and 2011 had a total capacity of 3000 MWe. This suggests an average PV installation size of about 20 kW. Using 20-kWe as the average installation size the data, we conclude that the experience curve of Figure 1 was built over about 3 million installations. It is not realistic for the CST to achieve this number of installations in the conceivable future due to much larger minimum CST installation sizes.

In spite of the difficulty of direct projections from the PV experience, the experience curve approach may still be valid for analysing future CST costs but I believe two important caveats must apply:

- Firstly, an experience curve based on cumulative installed CST capacity is not suitable because the CST learning experience is likely to increase in discrete steps from one installation to the next. This discretisation is valid for any technology but the effect can be neglected where installation sizes are relatively small, e.g. the PV industry. Since CST has to be built above a certain size, which is much larger than the average PV installation size, the installed MW capacity cannot be a proxy for CST learning experience. It is more appropriate to measure the CST experience in installation numbers.

- Secondly, one has to recognise the fact that the CST industry cannot possibly build up an experience curve over 3 million installations as PV industry has been doing over the last thirty years. Unlike PV, a CST power generator cannot be arbitrarily small. The major constraint is the power block. Most mature CST technologies today are based on the use of steam Rankine cycles. Steam power plants need to be above a minimum size to deliver acceptable performance. This minimum limit is about 50-MWe for today's mature CST systems. In this context, the economic power block size is not relevant to the solar field technology, which may be parabolic troughs, linear Fresnel systems or point receivers.

Even if he CST experience is based on installation numbers rather than megawatts, the question still remains on plausible PR values to make useful future predictions. The European ECOSTAR roadmap estimates a PR value around 0.86-0.88, predicting a cost reduction down to 5 cents/kWh, provided a total installed capacity of 40-GW is achieved between 2020 and 2025 (Figure 2).

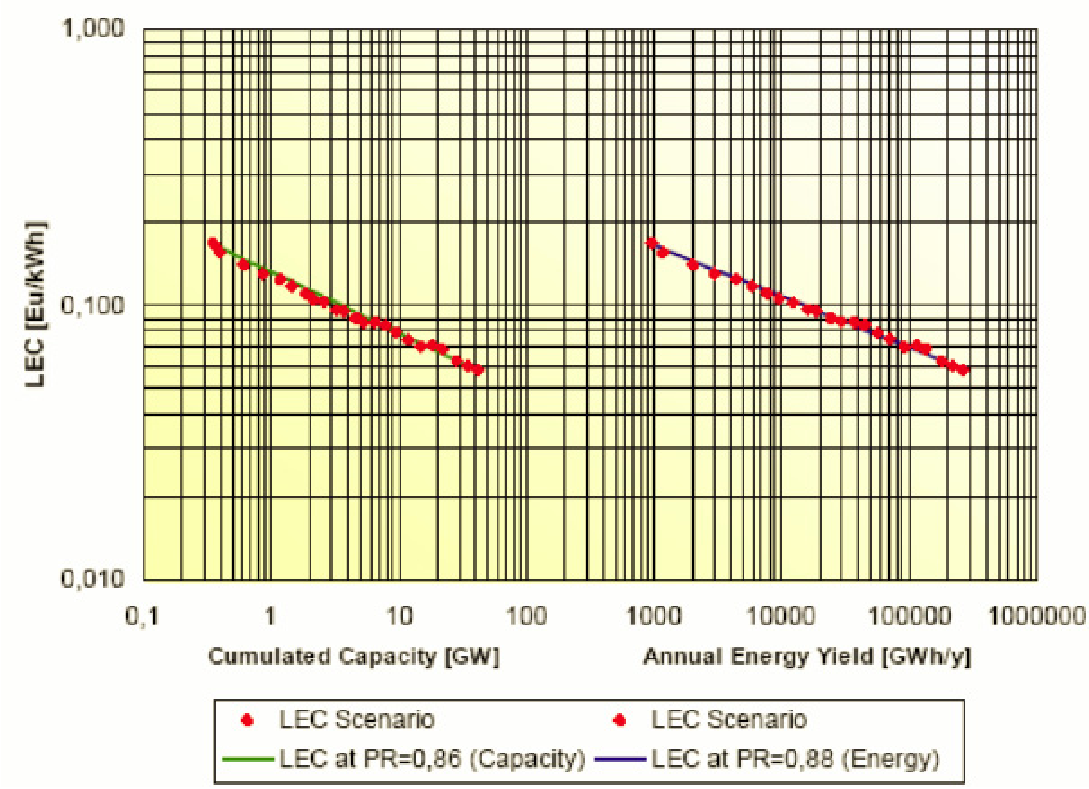

Figure 2. Scenario of reducing LEC for HTST electricity using learning curve approach[8]

3. How can the CST sector build up experience and reduce costs?

The roadmap plotted in Figure 2 projects a significant reduction in the cost of CST-generated electricity provided a total CST capacity of 40-GWe is built in five years. If the present cost of CST were competitive with the conventional power generation alternatives, it would not be difficult achieve this.

The levelised electricity cost (LEC) from CST varies over a range of 20 to 35 US cents/kWh (30-35 ¢/kWh according to AETA[9]; 20-26 ¢/kWh in the ECOSTAR roadmap[8]). The current cost of electricity using conventional coal-fired power generation is less than 5 US cents/kWh. This means that, if the new CST power plants are to generate electricity for a grid already being served by coal-fired power generation, the CST plants have to be subsidised by at least 15 US cents/kWh for every kWh they generate. As we are talking about an experience curve that will need to be generating billions of kWh every year (see Figure 2), if the new CST plants are to be commercially feasible in a market already served by coal-fired power generation, they have to enjoy a public subsidy starting with \$150m/year and increasing to over \$10b/year by 2025. This amounts to a large spending dedicated to building the CST experience curve over five years. It is certainly possible but at the present economic and political climate may not be likely to happen soon.

Therefore, we conclude that it is not realistic to expect the CST to build a substantial experience curve in power grids served by coal-fired power generation. However, there are other options. The first one is offered by the off-grid markets. At the first glance, these markets do not look too hard to penetrate. Electricity in off-grid markets is usually supplied by small generators burning diesel fuel at a cost in the range of 50 ¢/kWh to \$1/kWh [10]. This is significantly higher than the CST costs mentioned above. In other words, at the first glance, the CST should appear to be competitive against diesel generation in off-grid markets.

If the size of the off-grid market is large enough and if CST has appropriate products for these off-grid electricity markets, it may be easy to build up the experience curve in Figure 2 by initially serving the off-grid power sector. The conditions in the preceding statement warrant further consideration of off-grid market characteristics and the CST offerings for these markets.

3.1. Off-grid electricity markets

The off-grid market in Australia has two components:

- mining installations
- remote rural towns

Remote mining sites have high power requirements. For example, the specific energy consumption for extracting ore from the ground is reported to be 3-5 kWh/t for open cut copper mines and 12-40 kWh/t in underground copper mines in Australia[11]. Mineral processing has similar energy intensities, taking about 15-25 kWh/t to process the ore into a sellable product. Overall, the Australian mining industry consumes about 64 PJ or 17800 GWh of electricity in a year [12]. Generation of this electricity requires over 4000 MW of installed capacity at an assumed 50% capacity factor. A capacity factor of 50% is a reasonable estimate because the mining power demand is not uniform and the installed capacity needs to be large enough to respond to the highest peaks. Most Australian mines are located away from the grid and they have to have on-site generation to provide for their electricity needs, typically using diesel generators. Since the cost of unsubsidized diesel generation in remote sites could be as high as \$1/kWh[13], the CST power provides a competitive alternative. Moreover, compared to PV power, CST is easier to integrate with diesel- or gas-fired power generation with only a small amount of thermal storage.

It is not only in Australia that remote mining sites offer a potential market for CST. Many of the large mining operations around the world are located in areas with high DNI, e.g. sub-Saharan Africa, Northern Chile, as well as Australia[11].

So why has the CST industry not established a beachhead in this industry yet? There are two reasons. The first reason applies in Australia and possibly in other places and it is concerned with diesel fuel tax exemptions extended to the mining industry.

If the mine site diesel generators were paying the same price for diesel fuel that the city diesel generators were paying, then the diesel-generated electricity in mine sites would be too expensive and a number of renewable power alternatives would displace diesel fuel even at the current renewable power prices. The first reason for CST not being competitive against diesel fuel in remote mine sites is because mine sites pay less for their diesel fuel compared to what people pay in the cities. In Australia, mine sites do not pay the diesel fuel excise tax, which amounts to about 38 cents/liter or about 11 cents/kWh for a top-of-the-range diesel generator running at 35% efficiency (and higher for generators running at lower efficiencies). If that excise is added to the diesel fuel purchased by the mine site so that they pay the same tax that the city generators do, the mining companies would have a significant motivation to explore alternative means of power generation, including solar power.

However, we cannot blame the excise task only for the failure of CST to penetrate the remote mining market. The second reason is a current technological weakness of the CST industry.

Diesel excise exemption is important but not the sole reason why mine sites are not using CST to generate electricity. Even without the excise tax, the current price of diesel-fuelled electricity in remote sites could be as high as 25-50 cents/kWh, which is already in the CST cost range. Therefore, we have to conclude that the existence of diesel excise exemption is not enough to explain why the CST industry is unable to exploit this market. This brings us to our second reason, which is fortunately something we can address through appropriate technology as will be seen in the next section.

The current CST technology does not have a commercial product at the unit sizes required by the remote mine sites. Typical installed capacities in remote mining sites range from 5 to 10 megawatts. For example, two typical nickel mines in Western Australia, Cosmos and Sinclair, use diesel generators and the installed capacity is 12MW in Cosmos and 8MW in Sinclair. If these mine sites wanted to produce some or all of their electricity needs using CST, CST industry could not offer them a product producing electricity at the levelised cost near 50 cents/kWh. The minimum economical size for the current CST technologies is 50 MWe, although the CST system suppliers would prefer much larger unit sizes. The major constraint is the power block. Most mature CST technologies today are based on the use of steam Rankine cycles. Steam power plants need to be above a minimum size to deliver acceptable performance. This minimum limit seems to be about 50-MWe for today's mature CST systems. This is too large for remote mining sites, except in areas where a number of sites can be supplied from one hub, e.g. the town of Mount Isa in Australia.

It is important to realize that the economic size for the solar field is much smaller. If the power block can be manufactured at sizes corresponding to typical remote mine site requirements, i.e. in the range of 5-10 MWe, then the CST would be a commercially competitive product for those markets and this is true for a number of solar field technologies currently using steam cycles including both linear and point receiver systems.

The remote rural towns in Australia are also possible markets if CST power plants can be offered at sizes down to 1 MWe.

At the moment, these markets cannot be accessed by the CST industry because it is not easy to develop efficient steam turbine technology suitable for CST plants at the size range 1 to 10 MWe. A new type of power conversion technology is needed as described in the following section. Fortunately, a suitable technology, CST power generation using supercritical CO2 (sCO2) power cycles, has already been found as described in the next section.

3.2. Supercritical CO2 (sCO2) Cycles

The sCO2 has been proposed as an effective alternative to steam power block (e.g. [14], [15]) in the last five years and is now set as a 2020 goal in the US Sunshot program. Its main attraction is that the use of carbon dioxide instead of steam allows higher power-cycle efficiencies and cycle components that are more compact.

An important caveat is that the Sunshot program is aiming to develop utility-scale technologies. Therefore, it does not need to acknowledge the additional benefit of using supercritical CO2, which is the potential to enable the manufacture of small compact power blocks and smaller commercial CST power generators.

Supercritical CO2 power plants using radial turbines, can be built at sizes much smaller than steam turbines (down to 250-kWe but preferably in the range of 1-10MWe) without significant cost and efficiency penalties, e.g. see Turchi[14], Ma and Turchi[15], or the interview with Zarza[16]. Supercritical CO2 operated in a closed-loop Brayton cycle not only has the potential for equivalent or higher cycle efficiencies versus supercritical or superheated steam cycles at temperatures relevant for CSP applications but also offers a much more compact and simpler plant configuration[17, 18].

This makes it possible to answer the question posed earlier: how can the CST sector build up experience and reduce costs? The answer is supercritical CO2 systems. The CST sector can build up experience and reduce costs using supercritical CO2 instead of steam to convert the solar heat into electricity. Modular supercritical CO2 systems would make it possible to build up CST experience much faster by building many relatively small systems.

The ECOSTAR roadmap is based on a reference installation size of 50-MWe. For CST, it is arguable that the number of installations is a better unit for measuring experience than the installed capacity. The cost reduction projected in Figure 2 can be achieved over 800 installations. The same number of installations can be achieved on commercial terms and at no additional incentives by using sCO2 systems at the 1-10 MWe size range for remote mining sites and other remote communities.

4. Conclusions

In this paper, it has been argued that, in developing an experience curve, the number of commercial installations is more important than the cumulative installed capacity. The significance of this point can only be realized if commercial CST power generators can be offered at relatively small sizes, i.e. at sizes 5-10 MWe. The sCO2 systems have the potential to make this possible and will help the CST sector quickly develop a sizeable experience curve.

The main conclusions can be summarized as follows:

- The European ECOSTAR roadmap[8] predicts the CST costs to come down to 5 cents/kWh, if 40GWe of installed CST capacity can be achieved by building 800 plants at an average size of 50 MWe each.
- Since the CST experience is gained incrementally with each installation, the number of installations is a more relevant unit to measure experience than the cumulative generation capacity. Therefore, the ECOSTAR cost reduction projections can be expressed as an experience curve of 800 units independent of the unit size (provided the unit size is large enough to require a sufficiently large solar field).
- In Australia alone, the electricity requirement by the mining industry is 4000MWe of installed capacity and most of mining sites are remotely located relying on diesel generation.
- The sCO2 technology will make it possible to offer 5-MWe CST power plants to this market at commercially competitive costs.
- This will enable the CST power industry to quickly build up an experience curve over 800 commercial installations in Australia only, realizing cost reduction down to 5 cents/kWh as predicted in the European ECOSTAR roadmap[8].

Adding the global remote area markets in addition to Australian mining, it is plausible to expect the CST experience grow at a faster rate. The cost reductions to be realized through the remote area experience can then be translated to utility-scale systems without requiring substantial public subsidies. The transfer of technology is expected to be relatively straightforward because the only difference between the small (5-10 MWe) and the utility-scale (>50-MWe) power generators would be the type of the turbine: radial turbines for the small plants and axial turbines for the large utility-scale plants.

Acknowledgements

This research was performed as part of the Australian Solar Thermal Research Initiative (ASTRI), a project supported by the Australian Government, through the Australian Renewable Energy Agency (ARENA).

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